THRESHOLDS FOR IRRIGATION MANAGEMENT OF PROCESSING TOMATOES USING SOIL MOISTURE SENSORS IN SOUTHWESTERN ONTARIO

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ABSTRACT. *Processing tomato (*Lycopersicon esculentum *Mill.) is an economically important vegetable crop in southwestern Ontario. Processing tomato (cultivar H9553) fruit yield and quality were evaluated in field experiments in southwestern Ontario over a three-year period (2008-2010). A split-plot randomized complete block design with four blocks was used in 2008 and 2010. Irrigation types (buried and surface drip) served as the main plots, while four moisture depletion levels constituted the split plots. In 2009, a 2×4 factorial complete randomized block design with four blocks was used, with the same two factors. The moisture treatments represented the lower soil moisture triggers, which initiated irrigation scheduling. Irrigation was terminated for each treatment when field capacity was reached. Continuous soil moisture status over the growing season was monitored with a combination of volumetric and tensiometric sensors. Seven fruit quality parameters were monitored: fruit weight, color, pH, size, firmness, Brix yield, and soluble solids. In each year, the most stressed treatment produced the highest soluble solids (6.0, 4.8, and 5.2 °Brix for 2008, 2009, and 2010, respectively). Total and marketable fruit yields ranged from 91.9 to 121.1 Mg ha^{-1} and from 91.4 and 119.7 kg ha^{-1}, respectively. Statistical significance was obtained among treatments and irrigation types in 2008 only. Irrigation water use efficiency was also not statistically significant over the three years. Seasonal irrigation depth ranged from 58 to 196 mm, and statistical significance among the moisture treatments was obtained in 2008 and 2010.*

Keywords. *FDR, Irrigation scheduling, Irrigation thresholds, TDR.*

Agriculture is a key driver for the Canadian economy, providing one in seven jobs within the country. The agri-food sector accounts for 8.3% of Canada's gross domestic product, USD $26.5 billion of which comes from exports and employing nearly 2.1 million persons (AAFC, 2006). Canadian vegetable growers reported sales of USD $659 million in 2010, with two provinces (Ontario and Quebec) accounting for more than 80% of the vegetable sales (Statistics Canada, 2011). Vegetable and dry bean production is a critical part of the food and agriculture industry in Ontario. Virtually all of the tomatoes grown in Canada for processing are produced in Ontario, with the counties of Essex and Kent being the main producing areas. In 2008, 0.62 million tons of processing tomatoes were produced by 150 growers, generating over USD $60.5 million (OHCRSC, 2006). In most years, rainfall during the growing season is insufficient to attain optimum production (Warner et al., 2007). Tan et al. (2003) noted that, through the 1990s, rainfall during the growing season decreased by about 25 mm year^{-1}. The 30-year (1971 to 2000) climate normal rainfall for Windsor and London averaged 254.3 and 251.3 mm, respectively. Over the growing season, an average cultivar requires 400 mm of water (LeBoeuf et al., 2007). Thus, intensive tomato production in these two counties necessitates the use of supplemental irrigation to offset the deficiencies in rainfall to maintain high levels of production (Warner et al., 2007).

There is increasing pressure for more judicious utilization of limited water resources to reduce negative environmental impacts. Shock et al. (2001) identified economic competition in marketing produce, competition for water, and political pressure as the three forces to minimize off-site impacts of irrigation-induced runoff and leaching. It is desirable to optimize crop yield and quality under the constraints of reducing water use and increasing the efficiency of the use of agricultural chemicals.

Irrigation scheduling is a technique for timely and accurately application of water to a crop and is key to conserving water, improving irrigation performance, and ensuring the sustainability of irrigated agriculture (Thompson et al., 2007b). Several irrigation scheduling methods based on water budget, soil, and plant indicators have been used for different crops, with the water budget method probably the most widely used technique (Fareres et al., 2003). However, over the past decade, a new generation of soil moisture sensors based on electrical properties, such as resistance, capacitance, and time

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domain reflectometry, has been developed (Fares et al., 2006; Fereres et al., 2003). These sensors measure either soil matric potential or volumetric soil water content (Thompson et al., 2007b). Soil moisture sensors facilitate frequent but low-volume irrigation applications, which have been found to be superior to the traditional scheduling of fewer, large-volume applications. These devices have been used extensively for efficient irrigation and nutrient management in different crops (Fares and Alva, 2000; Lukangu et al., 1999; Thompson et al., 2007b).

Soil moisture sensors can be used as a standalone method to effect irrigation scheduling or in conjunction with other methods, such as the FAO and water budget methods (Thompson et al., 2007a, 2007b). However, optimal irrigation scheduling using soil moisture, whether soil matric potential or volumetric soil water content, necessitates accurate threshold values or indices for individual crops in a given agricultural system (Lukangu et al., 1999). The upper and lower thresholds are described as the fill and refill points, respectively, with the fill point corresponding to field capacity. The refill point is the soil moisture content below which crop growth is measurably decreased or where a crop begins to experience water stress (Campbell and Campbell, 1982).

For volumetric soil moisture content sensors, the available water content (AWC) is often used to determine the trigger or threshold for irrigation management (Thompson et al., 2007b). Since the AWC is the moisture available to the plant between field capacity and permanent wilting point, a management allowable depletion (MAD) ranging between 20% and 40% of AWC is often used as the refill threshold for different crops. FAO 56 provides guidelines on these levels and recommends a depletion of 40% for tomato (Allen et al., 1998). Hartz et al. (2005) added that tomatoes can tolerate a depletion of 20% to 30% of available soil moisture in the active root zone without having yield losses. It is also possible to establish threshold values for soil moisture sensors as a percentage of field capacity instead of the MAD, since the two are related. Shock et al. (2007) added that irrigation thresholds should be determined for site-specific conditions to account for variability in climate, soils, crop cultivars, and irrigation systems.

A range of threshold/refill values has been used for tension-based soil moisture sensors (Shock and Wang, 2011). Haise and Hagan (1967) used refill points of -60 to -70 kPa for high and low evaporative demand conditions for cabbages. Stanley and Maynard (1990) recommended soil water potential levels in the -10 and -30 kPa range for vegetables grown under irrigation with high and low evaporative demand, respectively. Thompson et al. (2007b) reported soil matric potential threshold values of -35 kPa for melon and -38 to -58 kPa for tomatoes. Marouelli and Silva (2007) tested tension threshold values between -5 and -120 kPa for processing tomatoes and found that soil moisture tension thresholds of -35, -12, and -15 kPa produced the highest yields for the vegetative, fruit development, and maturation growth stages, respectively.

Numerous studies have found that irrigation substantially increased fruit yield of processing tomato (Hanson et al., 2006; Patanè and Cosentino, 2010). Warner et al. (2007) obtained processing tomato yields ranging from 126.1 to 181.5 Mg ha^{-1} under different irrigation application rates as a function of ET_c (0.5 to 1.2 ET_c) for Harrow, Ontario. At the University of California, Johnstone et al. (2005) carried out drip irrigation experiments between 2000 and 2002 on processing tomatoes in loam soils, as a function of reference evapotranspiration, and found yields ranging from 78 to 125 Mg ha^{-1}. Drip irrigation experiments using varying amounts of potassium (from 0 to 600 kg ha^{-1}) produced total yields for processing tomatoes (cultivar H9478) ranging from 86.6 to 92.5 Mg ha^{-1} at Harrow, Ontario (Liu et al., 2011).

In the humid climate of southwestern Ontario, determining the optimum amount of water to apply to accurately meet crop water requirements, especially after a rainfall event, can be a challenge. To this end, the objective of this work was to use a combination of tension and volumetric based continuous soil moisture monitoring sensors as standalone devices to determine the optimum trigger point (refill) and to effect irrigation scheduling of field processing tomatoes grown in loamy sand soils.

Materials and Methods

Experimental Location

A three-year (2008 to 2010) field experiment was conducted during the summer months of May through September on a commercial farm in Leamington, in southwestern Ontario. The climate is classified as humid, with hot summers complemented by dry and cold winters. Average annual temperature and precipitation are approximately 9.5°C and 750 mm, respectively (Tan and Reynolds, 2003). The growing season for field processing tomatoes extends from mid-May to September, with average growing season maximum and minimum daily temperatures 24.9°C and 15.0°C, respectively, and average seasonal rainfall of approximately 261.1 mm. The rainfall is typically spread throughout the year, with no predominant rainy months. The dominant soil within the production zone (0 to 30 cm) is loamy sand (86% sand, 8% silt, and 6% clay) with an average bulk density of 1450 kg m^{-3}. Field soil water capacity ranged between 20% and 25% by volume. Chemical properties of the soil (0 to 30 cm) are provided in table 1. Agronomic soil test P and NO_3-N were determined using the Olsen P procedure (0.5 M $NaHCO_3$, pH 8.5; Olsen et al., 1954) and the 2.0 M KCl procedure (Keeney and Nelson, 1982), respectively.

Table 1. 2008-2010 pre-planting soil properties at the 0 to 30 cm depth at the experimental site.

Soil Parameter	2008	2009	2010
NO_3-N (ppm)	52	101	37
Available P (ppm)	144	121	154
Potassium (ppm)	243	219	191
pH	7.3	7.0	7.0
Organic matter (%)	2.1	2.9	2.9

Table 2. Experimental design over the three years (RCBD = randomized complete block design; FC = field capacity).

Year	Experimental Design	Factor 1: Irrigation Type		Factor 2: Moisture Level				Blocks
2008	Split-plot RCBD	Surface drip irrigation	Buried drip irrigation	60% FC	70% FC	80% FC	Tension base (-30 kPa)	4
2009	Factorial RCBD	Surface drip irrigation	Buried drip irrigation	74% FC	82% FC	91% FC	Tension base (-30 kPa)	4
2010	Split-plot RCBD	Surface drip irrigation	Buried drip irrigation	55% FC	70% FC	85% FC	Tension base (-30 kPa)	4

Experimental Design

Table 2 provides a summary of the experimental design over the three years. A split-plot randomized complete block design (RCBD) was used in 2008 and 2010, and a 2×4 factorial RCBD was used in 2009. The split-plot design involved two experimental factors. The irrigation types (buried and surface drip irrigation) and moisture levels (three moisture levels and a tension treatment) were assigned to the whole plot (main plot) and split plots, respectively. The factorial experimental design in 2009 had the same two factors. The volumetric moisture treatments were expressed as a fraction of field capacity (FC) and represented the depletion that the soil moisture reached to initiate irrigation scheduling. In 2009, the volumetric moisture treatments were changed from 60%, 70%, and 80% of FC to 74%, 82%, and 91% of FC. This was done to examine the effects of a less stressed irrigation scheduling program. In 2010, the moisture treatments were again changed to 55%, 70%, and 80% of FC. This was done to increase the range between moisture treatments, making it more practical for monitoring. The change in the experimental design from split-plot RCBD to a factorial design was due to the fact that the parameters involved in the experiment fitted both models, and it was felt opportune to change the model in one of the three years.

The experiment for each year had four blocks, with each block having eight plots, for a total of 32 plots (16 with buried drip irrigation and 16 with surface drip irrigation). Due to the annual crop rotation, the experimental site on the farm was changed each year. In 2008, the blocks were oriented across the beds. Each plot comprised adjacent twin beds (2 beds × 1.5 m × 7.5 m) with an area of 22.5 m^2 per plot and located between guard beds (1.5 m × 7.5 m) on either side. There was a 1.5 m buffer between blocks. In 2009 and 2010, the blocks were oriented along the beds. Each of the plots (treatments) per block comprised a single bed (1.5 m × 8.0 m) with an area of 12 m^2 per plot and located between guard beds (1.5 m × 8 m) on either side. The guard beds formed the separation between blocks, and there was a 1.5 m buffer between plots in the blocks.

One drip line (irrigation tape, Streamline 636 006 F, Netafim Irrigation, Inc., Fresno, Cal.) was aligned along the surface of each twin-row bed for the surface irrigated plots. For the buried irrigated plots, the drip lines were installed to a depth of 20 cm (in 2008) and 15 cm (in 2009 and 2010). The inline emitters were spaced 30 cm apart, with a flow rate of at 0.46 L h^{-1} at 55 kPa in 2008 and 0.68 L h^{-1} at 62 kPa in 2009 and 2010, providing a uniform soil wetting pattern. Each plot had the same number of emitters. The volume of water applied during each irrigation event to each plot was determined as the product of the irrigation duration and the flow rate per plot at the requisite water pressure. The equivalent irrigation depth was determined as the quotient of the irrigation volume and effective wetted area.

Cropping Details

Processing tomato (*Lycopersicon esculentum* Mill., cultivar Heinz H9553) was grown in the study area during the three years. Seedlings (42 days old) were transplanted in soil with water content near field capacity in the top 30 cm. Transplant dates were 29 May 2008, 25 May 2009, and 15 May 2010. The crop was harvested after 105 days in 2008 (on 10 Sept.), after 112 days in 2009 (on 14 Sept.), and after 101 days in 2010 (on 24 Aug.). The seedlings were spaced 42 cm apart within the two rows, and the rows were 50 cm apart. Each set of twin rows was centered on a 1.5 m wide raised bed. The plant density was 31,746 plants ha^{-1}.

Soil Moisture Sensors, Data Collection, and Sensor Calibration

Three types of soil moisture sensors were installed in the field for continuous data collection: a time domain reflectometer (TDR) (CS625 water content reflectometer, Campbell Scientific Inc., Logan, Utah), a frequency domain reflectometer (FDR) (EnviroSMART, Sentek Sensor Technologies, Stepney, Australia), and an electronic tensiometer (Irrolis Sense Tx, Hortau, Inc., Saint-Romuald, Quebec, Canada).

The TDRs were installed with the aid of an insertion guide. The procedure for installing the FDR access tubes and the FDR sensors onto the probe guide is explained in the Sentek manual (Sentek, 2003). The tensiometers were installed in the conventional manner. For irrigation scheduling purposes, the critical depths at which the three soil moisture sensors were monitored were 0 to 30 cm for the TDRs, 20 cm for the FDRs (which effectively measured the soil moisture content over the 5 to 25 cm depth), and 15 cm for the tensiometers. All sensors (or access tubes in the case of the FDRs) were installed 10 cm away from the centrally aligned drip line and 10 cm away from the nearest emitter to ensure consistency in data collection.

Some changes occurred during the 2009 and 2010 experimental seasons. In 2009, the critical monitoring depth for the TDRs was 5 to 25 cm. The top 5 cm of soil was removed (at the site of installation), and the sensor was installed at a 33.6° angle to the vertical plane. In 2010, only TDRs and tensiometers were installed in the experimental plots. The monitoring depth for the TDRs was reverted back to 0 to 30 cm. Also in 2010, an upgraded version of the Irrolis Sense Tx electronic tensiometer, called the Irrolis MultiSense Tx3 probe, was used.

All devices were equipped with wireless communication to transmit data from the field to an onsite computer. All volumetric sensors were connected to 12 solar-powered data loggers (model CR205/6, Campbell Scientific, Inc.). The data were scanned every 5 min and recorded every 15 min¸ hourly and daily. The data were retrieved from the CR205/6 using a computer and LoggerNet software (Campbell Scientific, Inc.). The electronic tensiometer data were transmitted in real-time by wireless signals to the onsite desktop computer, which was equipped with the requisite proprietary hardware and software. Meteorological data were collected from an on-site weather station from 1 May to 31 August in 2008, 2009, and 2010. The weather parameters measured included temperature, rainfall, relative humidity, solar radiation, and wind speed.

Generic calibration curves for the TDR and FDR sensors were developed for site-specific conditions over the rooting depth of the crop (0 to 30 cm) against measured volumetric data. The tensiometers were not calibrated. *In situ* field capacity measurements were determined using the combined procedures outlined by Peters (1965) and Ratliff et al. (1983).

IRRIGATION SCHEDULING

From the calibration curves for the TDR and FDR sensors, the upper and lower volumetric water content and sensor threshold values (in µs and SFU for the TDR and FDR, respectively) were determined. The predetermined upper and lower threshold values for the tension-based treatment were -10 and -30 kPa, respectively. For all the treatments, the upper threshold value was FC. The soil moisture sensors for all 32 plots were continuously monitored at a central location. When the soil moisture content for each plot (buried and surface drip irrigated) was depleted to its requisite moisture treatment threshold value, irrigation was initiated. Irrigation was terminated when the upper trigger (FC) moisture content was reached. The irrigation scheduling process for each plot was done throughout the growing season. The volume of irrigation and the equivalent irrigation depth applied during each irrigation event were determined for each plot throughout the irrigation scheduling program. The irrigation scheduling program was implemented throughout the irrigation season, which began on 7 July, 29 June, and 21 June and was terminated on 1 September, 31 August, and 15 August in 2008, 2009, and 2010, respectively. In addition to the preplanting and side-dressing nutrient applications, all plots were fertigated simultaneously during each of the three years and for the same duration.

CROP YIELD, CROP QUALITY, AND IWUE

The fruits were harvested approximately ten days after spraying ethrel. To evaluate fruit yield and quality, all the fruits were harvested from six plants (2008 and 2010) or from four plants (2009) in each sub-plot. Fruits were categorized into red, green, or cull and weighed to determine total and marketable yields. Marketable yield was obtained by subtracting the weight of the culled fruits from the total yield. A random sample from each plot was tested for soluble sugar content, pH, firmness, fruit size, and color. Total solids were determined as the product of soluble solids and harvestable yields. From each plot, a random sample of approximately 50 marketable fruits was used to determine average fruit weight (Warner et al., 2007). A random sample of approximately 20 marketable fruits from each plot was tested for firmness with the use of a penetrometer (model FT 0110, Facchini, Alfonsine, Italy). The penetrometer was equipped with a cylindrical pin, 5 cm long with a 2 mm diameter flat end. The average of two firmness measures was taken on each fruit at opposite sides of the equatorial zone. A random sample of 20 red ripe fruits from each plot was washed, skinned, deseeded, and made into a pulp. The soluble solids (°Brix) and pH were measured in the homogenized juice using a digital refractometer and pH meter, respectively. Irrigation water use efficiency (IWUE) was determined by the ratio of the marketable yield (kg ha^{-1}) and the total seasonal irrigation volume (m^3 ha^{-1}), including rainfall, and expressed as kg m^{-3} (Howell, 2001).

STATISTICAL ANALYSIS

Statistical analysis was performed on individual years of data. In both experimental design models, the blocks were considered random effects, while the irrigation types and the moisture levels (treatments) were fixed-effects parameters. Statistical analyses were performed using the PROC MIXED procedure of SAS (SAS, 2007), designed to fit mixed-effect models. Analysis of fruit yield, fruit quality, and irrigation parameters was done. Differences at $p < 0.05$ were considered statistically significant. Least squares means of fixed-effects parameters were pairwise compared at $p < 0.05$. Model assumptions (normal distribution, and consistent variance of error terms) were verified prior to carrying out the analysis.

RESULTS AND DISCUSSION

WEATHER PATTERNS AND CLIMATIC CONDITIONS

The weather data are summarized in table 3. There was no significant difference in the rainfall totals (3.5 mm difference) over the monitoring period in 2008 and 2009; however, the distribution was very different. In 2008, May and June had higher rainfall than July and August, while the opposite was true in 2009. A comparison with the 30-year climate normal (1971 to 2000) indicated that the summer months of 2008 and 2009 received 15% and 16% lower than normal precipitation, respectively. The 2010 monthly rainfall exceeded the normal rainfall for the growing season, with the exception of August. The 2010 total rainfall also exceeded the 30-year average by 42.7%. The average over the three years (May to August) was 261.2 mm. Zhang et al. (2010) also reported average rainfall of 291.8 mm over the growing period (May to Sept) in Harrow, Ontario, Canada.

Air temperature gradually increased from about 15°C at the beginning of May to about 30°C between June and mid-August, after which there was a gradual decrease toward the end of August for all three years. Just prior to planting in May 2010, there was a four-day period in which the

Table 3. Rainfall comparison to 30-year normal (1971-2000).

Month	Climate Normal (1971 to 2000) Rainfall (mm) London	Windsor	Actual Rainfall (mm) Leamington 2008	2009	2010	Difference from Normal (%, relative to Windsor) 2008	2009	2010	Average Temperature (°C) Leamington 2008	2009	2010
May	82.6	80.7	66.4	12.5	114.7	-18.7	-84.7	72.7	12.5	14.7	15.4
June	86.8	89.8	108.1	65.0	91.4	22.4	-26.4	1.8	20.6	18.8	21.1
July	82.2	81.8	30.6	34.4	135.5	-62.7	-58	57.8	22.7	20.1	24.4
August	85.3	79.7	9.5	98.6	16.9	-88.5	19.5	78.8	20.7	21.0	23.4
Total	254.3	251.3	214.6	210.5	358.5	-15.1	-16.7	42.7			

temperatures dipped below 15°C. Although the trends were similar in the three years, the average monthly, maximum, and minimum air temperatures showed some variation. Jones (2007) highlighted the fact that tomato is a day length neutral plant under conditions of short or long days, requiring optimum mean daily temperature of 18.5°C to 25°C for growth, with night temperatures between 18°C and 21°C. At the time of planting, these conditions were met.

Field Capacity and Available Water Content

The FC and permanent wilting point (PWP) for 2008 to 2010 were 20% and 9%, 22% and 9%, and 25% and 10% volumetric water content (VWC), respectively. The varying FC values obtained may be attributed to the changing organic matter content over the years due to crop rotation and land preparation. Hudson (1994) noted that within each textual group, as organic matter (OM) content increased, the volume of water held at field capacity increased at a much greater rate than that held at PWP. He further added that 1% to 6% OM by weight was equivalent to approximately 5% to 25% by volume and hence can have a significant effect on available water content (AWC). The AWC ranged between 10% and 15% θ_v and was within the range (9% to 15%) of values for the soil type, as provided by Schwab et al. (1993). Table 4 summarizes the FC and tension treatments over the three years as fractions of AWC. Doorenbos and Pruitt (1977) recommended a management allowable deficit (MAD) for tomatoes of 30% to 40% of AWC to facilitate maximum yields. In 2008 and 2010, two of the four treatments were within that range; in 2009, three of the four treatments were within that range.

Table 4. Treatments expressed as depletion of AWC.

Year	Treatment	AWC Depletion (% VWC)
2008	80% FC	36
	70% FC	54
	60% FC	73
	-30 kPa	24
2009	91% FC	15
	82% FC	30
	74% FC	45
	-30 kPa	22
2010	85% FC	25
	70% FC	58
	55% FC	75
	-30 kPa	20

Applied Water in 2008

The irrigation scheduling summary and statistical results are shown in tables 5 and 6. In 2008, irrigation duration was not statistically significant among moisture treatments, irrigation types, or the interaction between moisture treatment and irrigation type. However, statistical significance for irrigation events, equivalent depths, and irrigation volumes was obtained among the moisture treatments, but not among irrigation types nor for the interaction between irrigation type and moisture treatment.

The -30 kPa treatment represented the least stress treatment, corresponding to a soil moisture content of approximately 88% FC or 24% depletion in AWC. It invariably reached the trigger point more frequently than the other moisture treatments and therefore received the most irrigation. Further, the tension treatment represented a point measurement of moisture content at the 15 cm depth, as compared to the TDRs and FDRs, which reflected the integrated moisture content over the 0 to 30 cm and 15 to 25 cm depths, respectively. This shallower depth also meant that the tension treatment reached the trigger point more frequently.

The 70% FC treatment was irrigated for a longer duration, received more water, and was irrigated more frequently than the 80% FC treatment. Two factors contributed to this discrepancy. First, one of the eight 80%

Table 5. Irrigation scheduling summary per treatment.

	Treatment	Duration (h)	Volume Applied (L)	Equivalent Depth (mm)	Effective Rainfall (mm)	Total Irrigation Events
2008 Season Averages	60% FC	59.8	1464	114	167.2	12
	70% FC	81.9	2006	156	167.2	20
	80% FC	53.7	1317	103	167.2	17
	-30 kPa	88.1	2160	168	167.2	30
2009 Season Averages	74% FC	32.9	582	85	186	11
	82% FC	66.8	1182	173	186	16
	91% FC	73.6	1302	190	186	23
	-30 kPa	58.6	1036	151	186	27
2010 Season Averages	55% FC	22.5	399	58	294.2	4
	70% FC	39.9	705	103	294.2	7
	85% FC	70.0	1238	181	294.2	15
	-30 kPa	75.9	1342	196	294.2	18

Table 6. Statistical results of fixed effect parameters: Irrigation parameters (2008-2010).[a]

Irrigation Parameter	2008 Moisture Treatment (MT)	2008 Irrigation Type (IT)	2008 MT × IT	2009 Moisture Treatment (MT)	2009 Irrigation Type (IT)	2009 MT × IT	2010 Moisture Treatment (MT)	2010 Irrigation Type (IT)	2010 MT × IT
Irrigation duration	NS	NS	NS	NS	NS	NS	*	NS	NS
Total irrigation events	*	NS	NS	*	NS	NS	*	NS	NS
Irrigation equivalent depth	*	NS	NS	NS	NS	NS	*	NS	NS
Irrigation volume	*	NS	NS	NS	NS	NS	*	NS	NS

[a] NS = not significant; asterisk (*) indicates significance at $p \leq 0.05$.

FC plots recorded unusually high moisture content throughout the growing season and was only irrigated four times, as compared to an average of 17 times for the 80% FC treatment. The consistently high moisture content in that plot was due to a depression in the field, which allowed lateral movement of soil moisture to accumulate in the vicinity of the plot. Secondly, one of the 70% FC plots was irrigated 14 times more than the average 70% FC plot, while another was irrigated for 50 h more than the average 70% FC treatment.

Although the 80% FC treatment was irrigated more regularly than the 60% FC treatment, the average seasonal irrigation depth was higher for 60% FC than for 80% FC. This was due to a combination of factors. One of the factors was highlighted above, with reference to the high moisture content of one of the 80% FC plots. Secondly, one of the 60% FC plots was irrigated more frequently than the average 80% FC treatment. Thirdly, the fact that the 60% FC treatment represented a wider threshold range meant that the average duration of application per irrigation event for the 60% FC treatment was longer than for the 80% FC treatment.

Applied Water in 2009 and 2010

In 2009, the treatments reflected a less stressed irrigation scheduling program than in the 2008 experiment, resulting in statistical significance only for the irrigation events among the moisture treatments. There was no statistical significance among the irrigation types nor for the interaction between irrigation type and moisture treatment. The average seasonal irrigation volume per plot was less than in 2008 because the plot area was reduced by approximately 47%. The equivalent depth of irrigation applied increased with the increase of the FC treatments (from 74% FC to 91% FC) and decreased for the -30 kPa treatment. Despite higher effective rainfall in 2009 and less stressed irrigation treatments, the equivalent irrigation depths for two of the FC treatments were higher in 2009 than in 2008. In 2008, the rainfall was concentrated during the first two months of the growing season; as a result, more effective use was made of the rainfall. Therefore, the need for irrigation during the early part of the season was minimal. In 2009, the rainfall was concentrated toward the end of the growing season, and there was therefore more need to irrigate during the early season. Most of the rainfall was in August; by then, the crop was close to harvesting, and the need for irrigation was minimal. The August rainfall therefore was not used very effectively.

In 2010, the FC treatments were changed to reflect a larger range between treatments, which contributed to statistical significance between irrigation duration, irrigation events, equivalent depth, and irrigation volume among the moisture treatments. There was no statistical significance among the irrigation types and the interaction between irrigation type and moisture treatment. There was a consistent trend among the treatments, with the most stressed moisture treatment reaching the trigger point the fewest number of times and therefore receiving the least seasonal irrigation and the shortest irrigation duration. The reciprocal was obtained for the least stressed treatment. The FC treatments were monitored at 0 to 30 cm depth, and the tension treatment was monitored at 15 cm depth. The shallower soil depth at which the tension treatment was measured would account for it reaching the trigger point more frequently. The distribution and total depth of the effective rainfall over the growing season would have contributed to the fewer overall irrigation events for all the treatments.

Warner et al. (2007) reported seasonal irrigation depths ranging from 58 to 267.6 mm during a three-year experiment in Harrow, Ontario (average rainfall of 247.1 for June to August) for different surface drip irrigation treatments for processing tomatoes in Granby sandy loam. Machado and Oliveira (2005) also reported values of 243.1 to 560.9 mm for subsurface drip irrigation in Coruche, Portugal, in sandy soils, with rainfall over the growing season amounting to 76.1 mm. In both cases, irrigation was applied as a function of crop evapotranspiration.

Fruit Yields in 2008

Tables 7 and 8 summarize yield results and yield statistics. In 2008, the average fruit yield for the four treatments ranged from 91.9 to 121 Mg ha^{-1}. The highest and lowest average yields were from the 70% FC and 60% FC treatments, respectively. There was a direct relationship between seasonal irrigation depth and crop yield (fig. 1). As a result, statistical significance was obtained for total and marketable yields among moisture treatments as well as irrigation types. Pairwise comparisons between moisture treatments revealed statistical significance only between 60% FC and 70% FC, between 60% FC and -30 kPa, and between 70% FC and 80% FC, but not between 60% FC and 80% FC, nor between -30 kPa and 80% FC. No significant difference was found in the interaction between moisture treatment and irrigation type.

The 70% FC treatment represented a depletion of the AWC of approximately 54%, which was substantially lower than the 30% to 40% AWC recommended by Doorenbos and Pruitt (1977). It was therefore surprising that the 70% FC treatment produced the highest yield. A

Table 7. Fruit yields per treatment for 2008-2010 (SE = standard error).

Year	Treatment	Total Yield (Mg ha^{-1}) Mean	SE	Marketable Yield (Mg ha^{-1}) Mean	SE	Red Fruit Yield (Mg ha^{-1}) Mean	SE
2008	60% FC	91.9	8.6	91.4	8.6	80.3	8.6
	70% FC	117.8	9.5	117.0	9.3	107.2	9.0
	80% FC	95.9	8.7	95.3	8.6	88.6	8.5
	-30 kPa	114.1	5.2	114.0	5.2	107.0	4.1
2009	74% FC	102.5	3.2	99.8	2.7	98.5	2.8
	82% FC	104.7	4.2	102.1	4.4	100.9	4.4
	91% FC	101.6	3.3	98.0	3.3	97.8	3.2
	-30 kPa	105.3	3.3	102.9	3.2	102.3	3.3
2010	55% FC	104.4	5.4	102.0	5.6	90.6	8.6
	70% FC	110.0	6.9	107.1	6.9	99.7	7.1
	85% FC	119.1	5.0	115.9	5.4	110.8	5.8
	-30 kPa	121.1	6.0	119.7	6.2	114.0	6.3

Table 8. Statistical results of fixed effect parameters: yields (2008-2010).[a]

Production Characteristic	2008 Moisture Treatment (MT)	2008 Irrigation Type (IT)	2008 MT × IT	2009 Moisture Treatment (MT)	2009 Irrigation Type (IT)	2009 MT × IT	2010 Moisture Treatment (MT)	2010 Irrigation Type (IT)	2010 MT × IT
Total yield	*	*	NS	NS	NS	NS	NS	NS	NS
Marketable yield	*	*	NS	NS	NS	NS	NS	NS	NS
Reds	*	*	NS	NS	NS	NS	*	NS	NS

[a] NS = not significant; asterisk (*) indicates significance at $p \leq 0.05$.

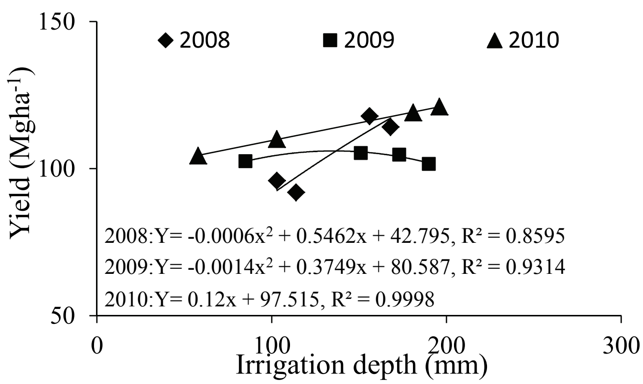

Figure 1. Irrigation depth vs. fruit yield for 2008 to 2010. *Y* = yield and *x* = irrigation depth.

review of the data revealed that two of the eight 70% FC plots had yields of 130.7 and 176.2 Mg ha^{-1}. The 176.2 Mg ha^{-1} plot was the highest yielding of the 32 plots and received the highest equivalent depth of irrigation (249.2 mm). These two exceptionally high yields therefore skewed the average yield for the 70% FC treatment, making it the treatment with the highest yield.

The 60% FC treatment represented a 74% depletion of the AWC. The plant physiological stress associated with the 60% FC treatment undoubtedly contributed to the lowest yields. The 80% FC treatment, which corresponded to 36% depletion in AWC, had unusually low yields. Five of the eight 80% FC plots had yields of less than 100 Mg ha^{-1} and resulted in an average yield that was lower than for the 70% FC treatment.

In relation to irrigation type, all the surface drip irrigated treatments produced higher yields than the corresponding buried drip irrigated treatments in 2008. This difference was attributed to the depth of the buried drip lines. During the 2008 season, the buried drip lines were installed at 20 cm below the surface; however, in 2009 and 2010, they were installed at 15 cm below the surface. Processing tomato has an effective rooting depth of approximately 30 to 40 cm in loamy sand. It was believed that the drip line placement at 20 cm depth may have limited the wetting pattern and the capillary rise during irrigation, limiting the amount of water available to the crop within the rooting zone, particularly between the 0 to 10 cm depths. Visual observations indicated that the soil surface for the buried drip irrigated plots were often dry, which may have been due to low capillary rise. However, the surface irrigated plots provided a longer period for the irrigation water to move through the root zone, and by extension supplied a greater amount of water at the effective rooting depth of 30 cm. This undoubtedly contributed to the significant difference between the yields of the irrigation types. Tan et al. (2003) reported similar trends but attributed the higher yields for surface irrigated plots to root intrusion into the subsurface emitters, preventing uniform water distribution. Phene et al. (1987) reported conflicting results for surface and buried (45 cm below the surface) drip irrigated processing tomatoes grown in clay loam soils in California. Manual and machine harvest yields for subsurface drip treatments were 10.3% and 17% greater, respectively, than for high-frequency surface drip treatments, and 29.2% and 24.1% greater than for low-frequency surface drip treatments. However, it must be noted that both the soil type and the depth of the drip lines were different in the current experiment.

FRUIT YIELDS IN 2009 AND 2010

In 2009, the average fruit yield for the four treatments ranged from 101.6 to 105 Mg ha^{-1}. The highest and lowest average yields were from the -30 kPa and 91% FC treatments, respectively. There was very little variation in yields between treatments during the 2009 season; therefore, no statistical significance was obtained among the moisture treatments, irrigation types, or the interaction between the two. This was primarily due to the fact that the soil moisture depletion levels of the four treatments were reduced, such that three of the four treatments were within the MAD of 30% to 40% AWC. The fourth moisture treatment (74% FC) was just 5% outside the range of the MAD recommended by Doorenbos and Pruitt (1977) and had approximately the same average yield as the 91% FC treatment. This may be due to the masking effect of the effective rainfall (186 mm), which would have minimized the effect of the 74% FC treatment particularly. The 91% FC treatment (depletion of 15% AWC) also had a lower yield than the -30 kPa treatment (depletion of 22% AWC). It is possible that the 91% FC treatment created too wet a soil environment in the rooting zone, thus negatively impacting plant growth and development, resulting in a slightly lower plant yield. Figure 1 indicates that the maximum yield was reached with a seasonal irrigation depth of approximately 150 mm. After this point, fruit yield decrease with increase irrigation.

In 2010, the average fruit yield ranged from 104.4 to 121.1 Mg ha^{-1}. The two treatments that fell within the MAD range of 30% to 40% AWC had higher yields, while the two treatments that fell outside the MAD range had lower yields. The 2010 season produced the highest average yields among the treatments (113.7 Mg ha^{-1}). It is strongly believed that the large effective rainfall depth over the growing season (May to August, with each month having greater rainfall than its 30-year average, and the seasonal average being 43% greater than the 30-year average) masked the effects of the treatments and thus reduced the plant stress, particularly during the critical plant growth stages. It is therefore not surprising that there were no statistical differences between moisture treatments, irrigation types, or the interaction between them.

The results over the three years indicated a direct relationship between irrigation volume and yield (fig. 1). Total and marketable production increased with increasing irrigation depth. Similar results were reported by Machado and Oliveira (2005), Machado et al. (2000), and Sezen et al. (2010) for both surface and buried drip irrigation. Machado and Oliveira (2005) obtained comparable yields, ranging from 78.8 to 141.7 Mg ha^{-1} and from 69.9 to 130.1 Mg ha^{-1} for total and marketable yields, respectively. Warner et al. (2007) reported total and marketable yields of 130 to 173.3 Mg ha^{-1} and 126.7 to 168.5 Mg ha^{-1}, respectively. Zhang et al. (2010) reported total and marketable yields of 64 to 166.7 Mg ha^{-1} and 56 to 138 Mg ha^{-1}, respectively. In each of the three years, the treatments with ≤40% AWC depletion generally produced higher yields, thus validating the recommendation of Doorenbos and Pruitt (1977). The -30 kPa treatment represented depletion in the AWC ranging from 22% to 24% VWC over the three years. Apart from the anomaly in 2008, when the 70% FC treatment had the highest yield, the tension treatment had the highest yields in 2009 and 2010, despite not being statistically significant. The threshold values (-10 and -30 kPa) for the fill and refill levels were comparable to other studies done with processing tomatoes. Marouelli and Silva (2007) used soil water thresholds (SWT) ranging from 5 to 120 kPa and found that the best yields were obtained when irrigation was performed at SWT thresholds of 35, 12, and 15 kPa during the vegetative, fruit development, and maturation growth stages, respectively, at Embrapa Vegetables, in Brasília, Brazil. Hartz and Hanson (2005) recommended thresholds in the range of 20 to 35 kPa up to fruit maturation and a range of 40 to 50 kPa after this point. However, these values were for deep clayey soils in California. It is also worth noting that while these researchers varied the threshold values over the developmental stages of the crop, the current experiment kept the threshold values constant throughout the growing season.

Fruit Quality and IWUE

Fruit Quality in 2008

Fruit quality parameters and their statistics are summarized in tables 9 and 10. In 2008, the average fruit weights from the different treatments reflected a trend similar to that of yields and had similar statistical results. Two of the seven fruit qualities parameters (weight and soluble solids) indicated statistical significance among the treatments and were influenced by the irrigation scheduling program and the irrigation depths for the various treatments over the season. All other fruit quality factors indicated no statistical significance. In relation to irrigation type, there was statistical significance for fruit weight, firmness, soluble solids, and Brix yields, which may be attributed to the fact that the surface irrigated plot received more irrigation than the buried irrigated plots. There was no statistical significance for the interaction between moisture treatment and irrigation type for all seven fruit quality parameters.

Table 9. Fruit quality parameters per treatment from 2008 to 2010 (standard errors shown in parentheses).

Year	Treatment	Weight (g)	Firmness (MPa)	Area (cm^2)	Color (Agtron)	Soluble Solids (°Brix)	pH	Brix Yield (Mg ha^{-1})	IWUE (kg m^{-3})
2008	60% FC	39.7 (1.2)	2.31 (0.04)	16.1 (0.8)	18.7 (0.5)	6.0 (0.2)	4.2 (0.01)	5.38 (0.3)	30.57 (2.2)
	70% FC	43.9 (2.0)	2.25 (0.06)	16.5 (0.4)	18.3 (0.5)	5.2 (0.2)	4.3 (0.01)	5.96 (0.2)	34.50 (1.8)
	80% FC	40.3 (1.4)	2.29 (0.05)	15.2 (0.5)	18.1 (0.8)	6.0 (0.2)	4.2 (0.01)	5.74 (0.6)	33.13 (2.8)
	-30 kPa	45.4 (2.0)	2.23 (0.06)	16.6 (0.4)	17.7 (0.5)	5.3 (0.2)	4.3 (0.01)	5.96 (0.1)	32.15 (1.2)
2009	74% FC	-	2.03 (0.05)	14.1 (0.4)	19.6 (0.4)	4.8 (0.1)	4.3 (0.01)	4.81 (0.1)	37.56 (1.9)
	82% FC	-	1.88 (0.06)	14.8 (0.1)	19.7 (0.3)	4.7 (0.1)	4.3 (0.01)	4.77 (0.2)	31.77 (4.2)
	91% FC	-	1.85 (0.05)	14.7 (0.3)	19.9 (0.5)	4.5 (0.1)	4.3 (0.01)	4.44 (0.2)	28.10 (2.9)
	-30 kPa	-	1.89 (0.04)	15.0 (0.3)	19.9 (0.4)	4.6 (0.1)	4.3 (0.01)	4.76 (0.2)	30.85 (1.4)
2010	55% FC	45.1 (1.9)	2.68 (0.09)	15.9 (0.4)	18.8 (0.6)	5.2 (0.2)	4.2 (0.01)	5.22 (0.2)	28.90 (1.1)
	70% FC	50.7 (1.7)	2.59 (0.12)	17.3 (0.3)	18.6 (0.4)	4.9 (0.2)	4.3 (0.01)	5.15 (0.3)	27.13 (1.9)
	85% FC	54.1 (1.6)	2.73 (0.11)	18.0 (0.2)	18.3 (0.4)	4.5 (0.1)	4.3 (0.01)	5.22 (0.2)	24.55 (1.2)
	-30 kPa	56.3 (2.4)	2.74(0.08)	18.6 (0.5)	18.0 (0.4)	4.5 (0.1)	4.3 (0.00)	5.38 (0.3)	24.41 (1.2)

Table 10. Statistical results of fixed effect parameters: Fruit quality (2008-2010).[a]

Production Characteristic	2008 Moisture Treatment (MT)	2008 Irrigation Type (IT)	2008 MT × IT	2009 Moisture Treatment (MT)	2009 Irrigation Type (IT)	2009 MT × IT	2010 Moisture Treatment (MT)	2010 Irrigation Type (IT)	2010 MT × IT
Fruit weight	*	*	NS	NA	NA	NA	*	NS	NS
Fruit firmness	NS	*	NS	NS	NS	NS	NS	NS	NS
Fruit area	NS	NS	NS	NS	NS	NS	*	NS	NS
Fruit color	NS	NS	NS	NS	NS	NS	*	NS	NS
Soluble solids	*	*	NS	NS	NS	NS	*	NS	NS
Fruit pH	NS	NS	NS	NS	NS	NS	NS	NS	NS
Brix yield	NS	*	NS	NS	NS	NS	NS	NS	NS
IWUE	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] NA = not available; NS = not significant; and asterisk (*) indicates significance at $p \leq 0.05$.

FRUIT QUALITY IN 2009 AND 2010

In 2009, individual fruit weight was not measured due to unavailability of equipment. All six fruit quality parameters indicated no statistical significance among the moisture treatments, irrigation types, or the interaction between the moisture treatment and irrigation type. Three factors contributed to the absence of statistical significance in 2009. First, the 2009 moisture treatments reflected a less stressed moisture irrigation scheduling program than the 2008 and 2010 treatments. The range between FC treatments was very small, and hence the differences were minimal. Three of the four moisture treatments were within the 30% to 40% MAD range, and the other (74% FC) represented a depletion in the AWC of 45%. The second factor was the depth at which the buried drip lines were installed in 2009. The drip lines were raised by 5 cm, to a depth of 15 cm below the soil surface, which facilitated better moisture distribution and improved yields for the buried drip irrigated plots as compared to 2008. The third factor was the relatively effective rainfall over the growing season, which masked the treatment effects, particularly for the 74% FC treatment.

In 2010, the range between the FC treatments was increased; as a result, greater differences were realized in the fruit quality parameters among the moisture treatments. Four of the seven fruit quality parameter (weight, size, color, and soluble solids) indicated statistical significance between the moisture treatments. There was no statistical significance among the irrigation types and the interaction of moisture treatment and irrigation type. As was the case in 2009, the shallower depth of the drip lines accounted for the improved yields for the buried irrigated plots, compared to the surface drip irrigated plots, which resulted in the absence of statistical significance among irrigation types.

Over the three years, both irrigation depth and fruit yield had converse effects on soluble solids (figs. 2a and 2b). Fruit weight and fruit size showed positive relationships with irrigation depth, while fruit firmness showed an inverse relationship with irrigation depth. Fruit pH showed no real relationship with moisture content (figs. 2c and 2d). In all three years, there was a negative relationship between irrigation depth and soluble solids. A negative correlation was also obtained between fruit yield and soluble solids in 2008 and 2010. A similar negative correlation was reported

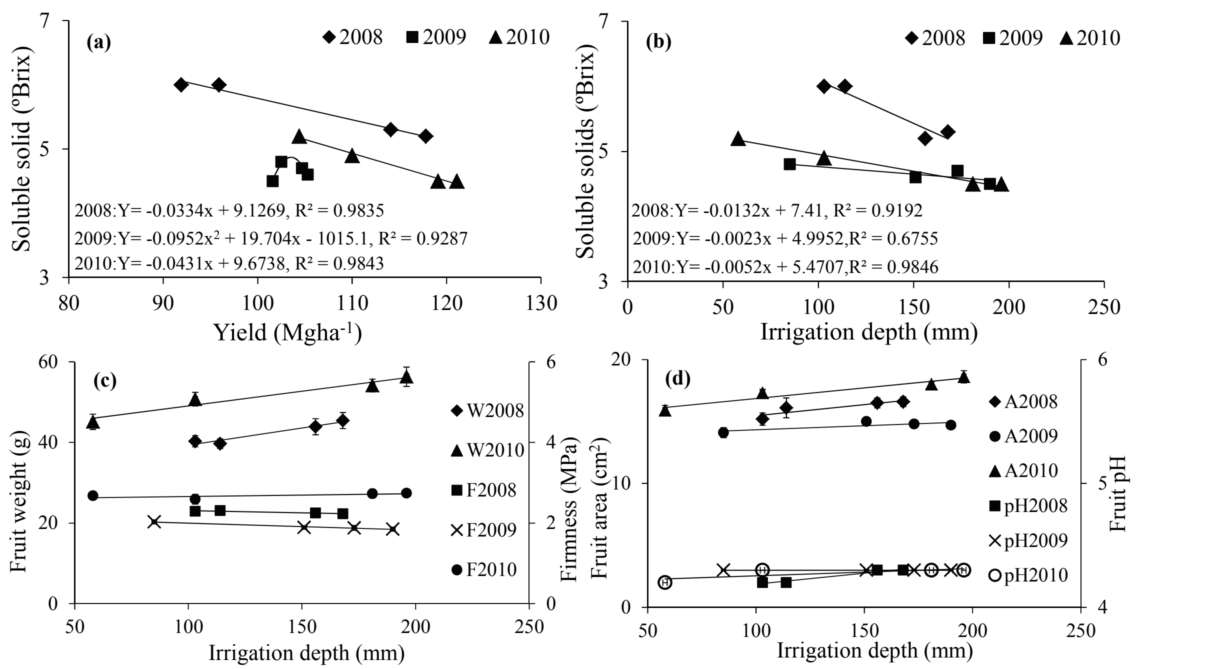

Figure 2. (a) Yield vs. soluble solids, (b) irrigation depth vs. soluble solids, (c) irrigation depth vs. fruit weight (W) and firmness (F), and (d) irrigation depth vs. fruit area (A) and pH. In 2a and 2b, *Y* = soluble solids and *x* = yield and irrigation depth for 2a and 2b, respectively. In 2c and 2d, error bars are standard errors of means.

by Machado and Oliveira (2005). In 2009, the soluble solids increase with increasing irrigation to a critical irrigation depth (150 mm) and subsequently decreased with increasing irrigation. It was found that pH was not statistically affected by irrigation depth, type, or treatment interaction. This was consistent with observations by Machado et al. (2003) and Davis et al. (1985). The Brix yield, which is the product of fruit soluble solids and the marketable yield, ranged from 4.77 to 5.96 Mg ha^{-1} over the three years. Statistical significance was realized only between irrigation types for 2008. This was attributed to the large difference in yield between the irrigation types. Machado and Oliveira (2005) reported soluble solids, pH values, and Brix yields ranging from 4.51 to 6.07 °Brix, from 4.30 to 4.38, and from 4.20 to 5.85 Mg ha^{-1}, respectively, which were comparable with the ranges reported in this research.

A possible water conservation approach to large-scale processing tomato production in Canada is to remunerate tomato growers based on soluble solids content (SSC). High SSC values are highly desirable for processing, and processors pay a premium for tomatoes with a high SSC (Dumas et al., 1994; Iddo, 2008). A practical approach would be to establish a threshold Brix yield, which can be achieved by setting a slightly higher fruit SSC. This would necessitate a reduction in irrigation water application, which would inevitably result in a slight decrease in yield. However, the net Brix yield would be the same. The savings to the grower would be in reduced irrigation cost. The unused surplus water could be used for further expansion. However, further research work is this area is necessary in a Canadian context.

The IWUE ranged from 30.5 to 35 kg m^{-3}, from 28.10 to 37.6 kg m^{-3}, and from 24.4 to 28.9 to kg m^{-3} for 2008, 2009, and 2010, respectively. In 2008, the 70% FC treatment yielded the highest IWUE (table 9). This was due to the unusually high yield for the 70% FC treatment. The 2008 IWUE showed a positive relationship with irrigation depth (fig. 3). Both of these factors can be attributed to the unusually higher yields for the 70% FC treatment. In 2009 and 2010, the lowest moisture treatment produced the highest IWUE due to the comparatively lower irrigation depth. Both of these years showed a converse relationship with irrigation depths, such that an increase in irrigation depths resulted in a corresponding decrease in IWUE. Although the effective rainfall was substantial over the three years, the IWUE was not significantly affected by moisture treatment, irrigation type, or their interaction. This trend is in agreement with Machado and Oliveira (2005), who reported IWUE values ranging from 20.2 to 22.8 kg m^{-3}. These values are substantially lower than that obtained in this research and are attributed to the higher water applied (irrigation and rainfall), which ranged from 326.2 to 644.0 mm.

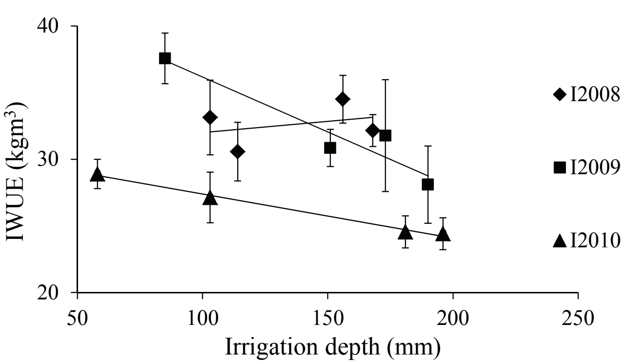

Figure 3. Irrigation depth vs. IWUE for 2008 to 2010. Error bars are standard errors of the means.

CONCLUSIONS

In southwestern Ontario, irrigated agriculture is a prerequisite for large-scale field tomato production. Commercial yield was higher for the moisture treatments in which the greatest quantity of water was applied. This also corresponded to the moisture treatments in which the depletion level in soil moisture was ≤40% AWC. The tension-based treatment (-30 kPa) produced the highest yields in two of the three years of the experiment. The 2008 results indicated that surface drip irrigation produced significantly higher yields than buried drip irrigation for each of the moisture treatments, which was attributed to the depth of the buried drip lines in 2008. However, in the other two years (2009 and 2010), there was no statistically significant difference in yield between the surface drip and buried drip irrigated plots after the buried drip lines were raised from 20 to 15 cm depth. The rainfall distribution, particularly during the critical growth periods of the crop, may have contributed by masking the moisture treatments and reducing crop stress. The fruit quality parameters of greatest interest were weight, size, firmness, soluble solids content, and Brix yield. The heavier and larger fruits were associated with the wetter moisture treatments. Brix yield showed statistical significance only between the surface and buried irrigation systems in 2008. The IWUE showed no statistical significance between the moisture treatments, irrigation types, or their interaction for each of the three years; however, 2010 had the lowest IWUE, which was due primarily to higher rainfall than in the previous two years. As a water conservation approach for large-scale processing tomato production in Canada, it is worth exploring the possibility of remunerating tomato growers based on soluble solids content (SSC) and Brix yield instead of on total yields.

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